The OBPG Ocean Surface PAR Product: Evaluation and Future Improvements

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EVALUATION AGAINST IN-SITU MEASUREMENTS

-The OBPG ocean surface PAR algorithm/product has been evaluated against in situ measurements in various regions:

- COVE platform off the west coast of the US, 2 PAR sensors, 36.9N-75.7W (2003-2015).
- BOUSSOLE buoy, Mediterranean Sea, 43.4N-7.90E (2009-2015).
- CCE1 and CCE2 moorings off the California coast, 33.5N-122.5W and 24.4N-120.8W (2009-2015 and 2011-2015).
- Field campaigns in the Arctic, 50-80N, NOW, MALINA, ArcticNET, TARA, VITALS (1998-2014).

Comparison of reference RT codes (Monte Carlo, ARTDECO, 6S), clear sky

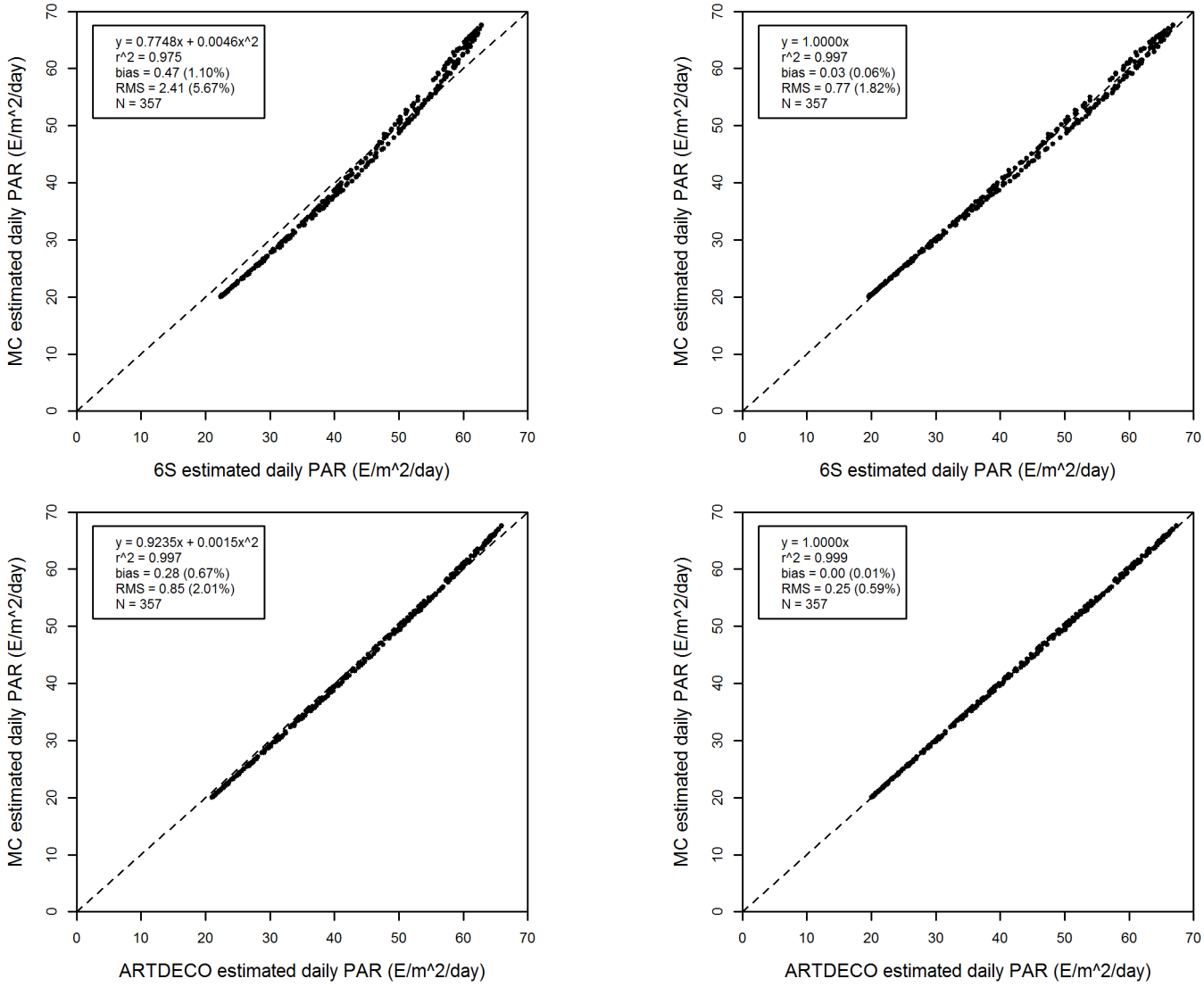


***Figure 1**: Comparison between daily PAR from Monte Carlo and ARTDECO and 6S codes at COVE site, clear sky conditions. AOT and Angstrom coefficient from MODIS.*

Comparison of MERIS 2.1 and MODIS v2.1 with Monte Carlo, clear sky

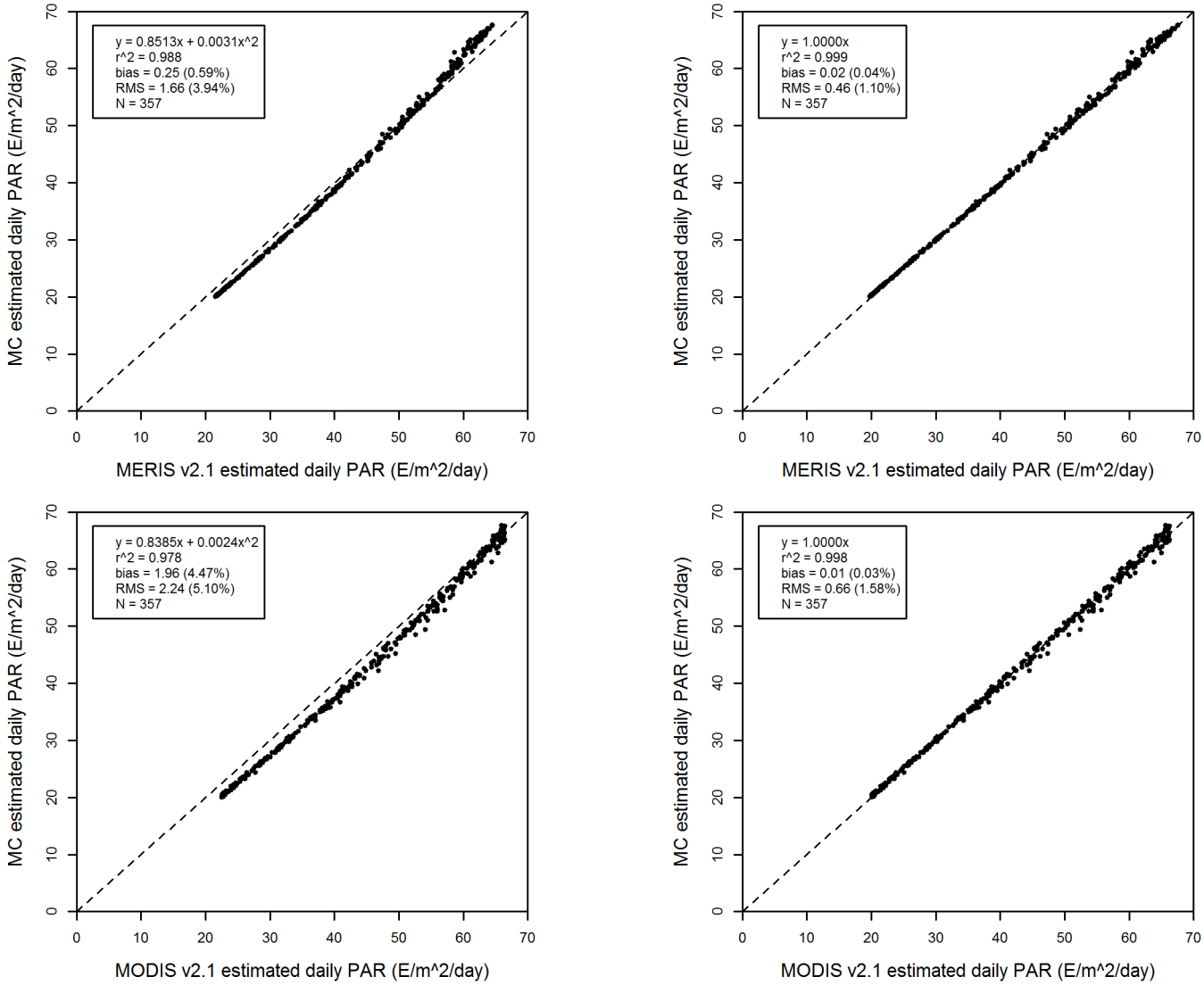


***Figure 2**: Comparison between daily PAR from Monte Carlo and MERIS v2.1 and MODIS v2.1 at COVE site, clear sky conditions. AOT and Angstrom coefficient from MODIS.*

Comparison of SeaWiFS 2.1 and VIIRS v2.1 with Monte Carlo, clear sky

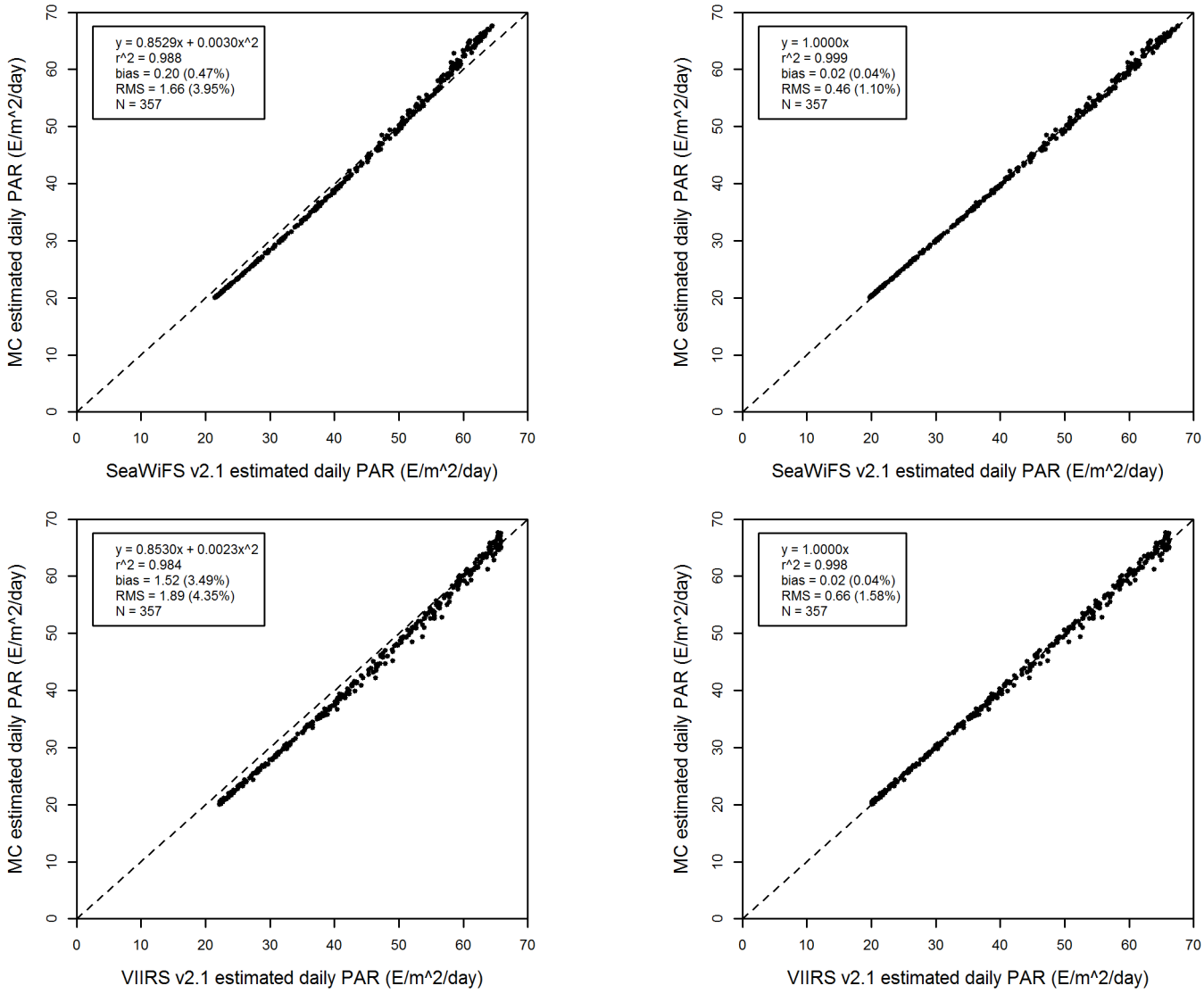


***Figure 3**: Comparison between daily PAR from Monte Carlo and SeaWiFS v2.1 and VIIRS v2.1 at COVE site, clear sky conditions. AOT and Angstrom coefficient from MODIS.*

***Table 1a**: PAR comparison statistics, Monte Carlo versus 6S, ARTDECO, MERIS v2.1, MODIS 2.1, SeaWiFS 2.1, and VIIRS 2.1, COVE site, clear sky.*

	r^2	bias	Percent bias	RMS	Percent RMS	N
MC vs 6S	0.975	0.47	1.10%	2.41	5.67%	357
MC vs ARTDECO	0.997	0.28	0.67%	0.85	2.01%	357
MC vs MERIS v2.1	0.988	0.25	0.59%	1.66	3.94%	357
MC vs MODIS v2.1	0.978	1.96	4.47%	2.24	5.10%	357
MC vs SeaWiFS v2.1	0.988	0.20	0.47%	1.66	3.95%	357
MC vs VIIRS v2.1	0.984	1.52	3.49 %	1.89	4.35%	357

***Table 1b:** Same as Table 1a, but after correction.*

	r^2	bias	Percent bias	RMS	Percent RMS	N
MC vs 6S	0.997	0.03	0.06%	0.77	1.82%	357
MC vs ARTDECO	0.999	0.00	0.01%	0.25	0.59%	357
MC vs MERIS v2.1	0.999	0.02	0.04%	0.46	1.10%	357
MC vs MODIS v2.1	0.998	0.01	0.03%	0.66	1.58%	357
MC vs SeaWiFS v2.1	0.999	0.02	0.04%	0.46	1.10%	357
MC vs VIIRS v2.1	0.998	0.02	0.04%	0.66	1.58%	357

Comparison of OBPG and v2.1 models, clear sky

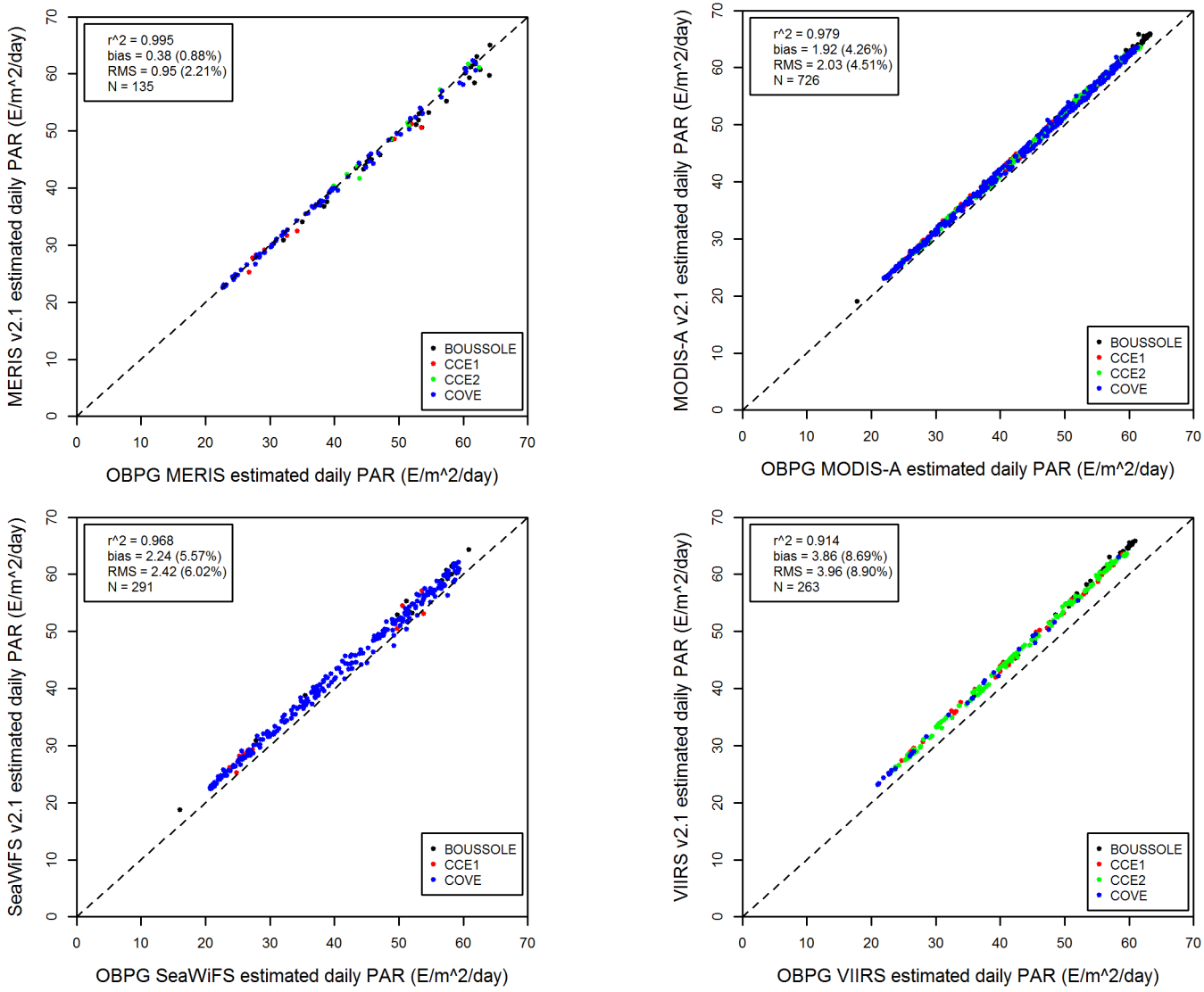


***Figure 4**: Comparison of OBPG and v2.1 daily PAR models at COVE, CCE-1, CCE-2, and BOUSSOLE sites, clear sky conditions.*

Comparison statistics for daily PAR from Monte Carlo vs. in situ data

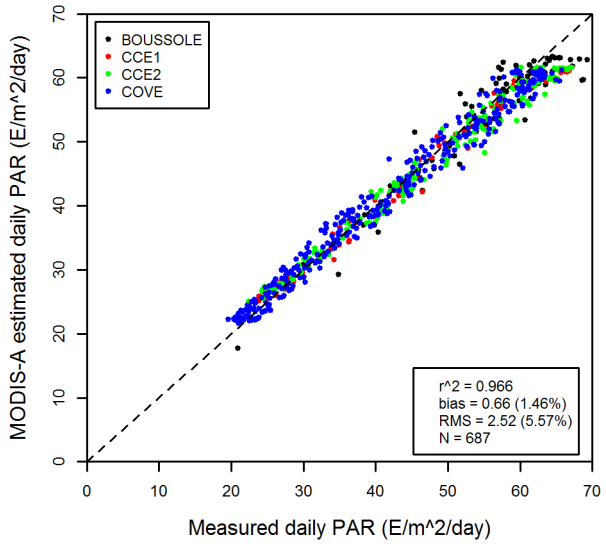
***Table 2a**: Daily PAR comparison statistics, Monte Carlo calculations vs. in situ measurements at COVE, CCE-1, CCE-2, and BOUSSOLE sites, clear sky, AOT<0.1 in near infrared. AOT, Angstrom coefficient, amount of gas absorbers from MODIS.*

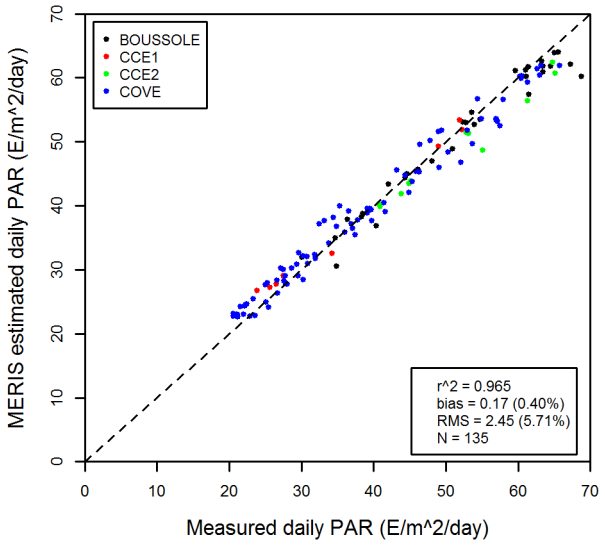
	r^2	bias	Percent bias	RMS	Percent RMS	N
BOUSSOLE	0.800	3.09	5.82%	4.67	8.79%	98
CCE1	0.975	0.96	2.05%	2.38	5.08%	106
CCE2	0.956	1.62	3.38%	2.90	6.06%	202
COVE	0.937	2.31	5.82%	3.82	9.65%	357

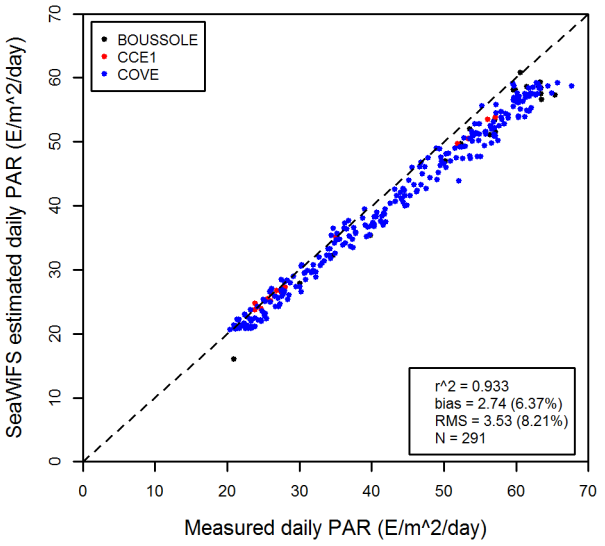
***Table 2b**: Same as Table 2a, but after linear correction.*

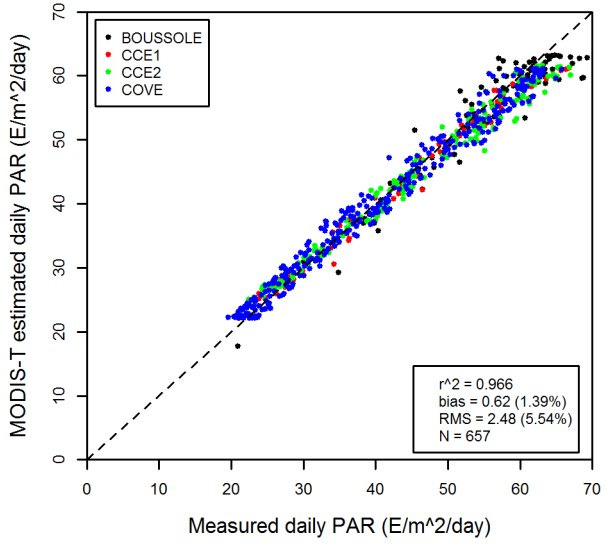
	r^2	bias	Percent bias	RMS	Percent RMS	N
BOUSSOLE	0.900	0.06	0.11%	3.30	5.87%	98
CCE1	0.985	0.01	0.01%	1.81	3.81%	106
CCE2	0.979	0.01	0.02%	2.03	4.10%	202
COVE	0.981	0.01	0.03%	2.10	5.00%	357

Comparison of OBPG daily PAR with in situ data (MC-corrected), clear sky









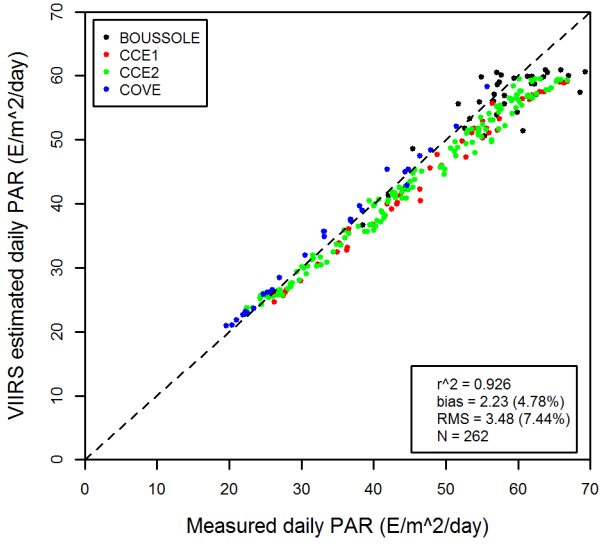
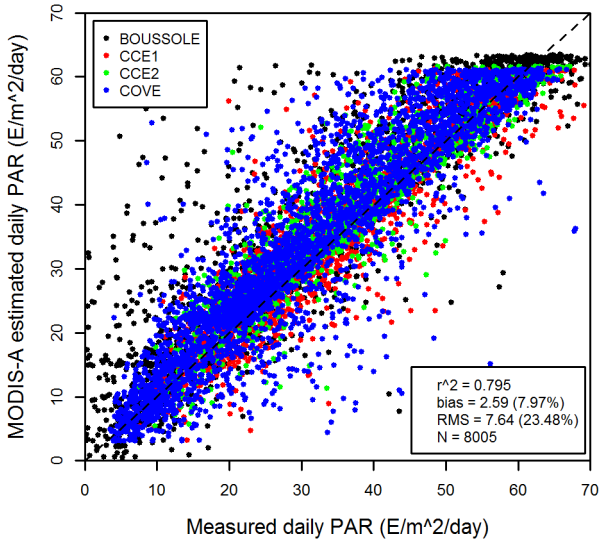
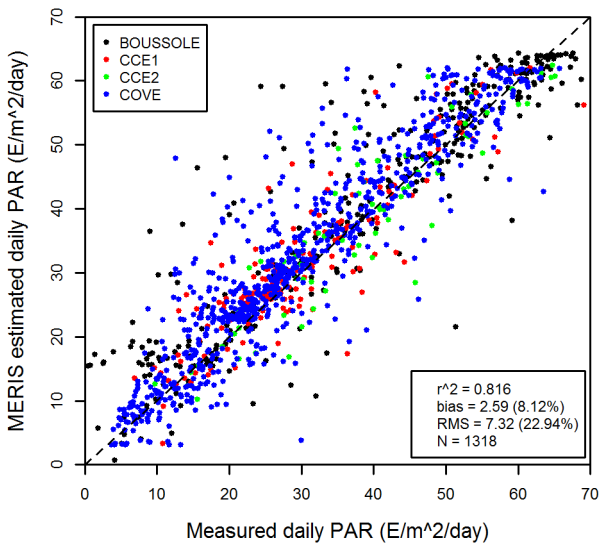
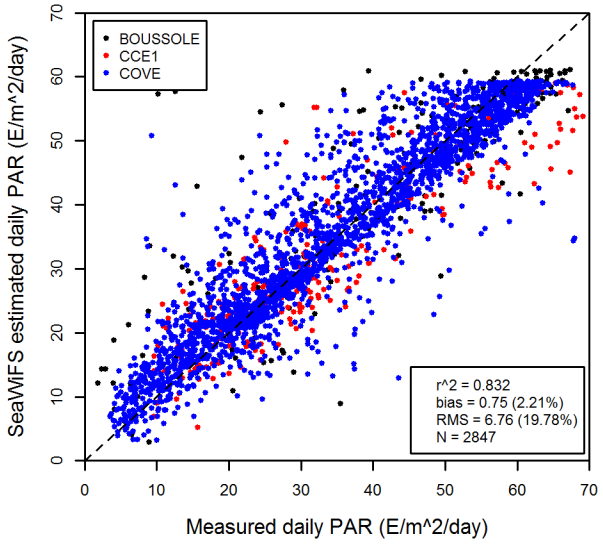


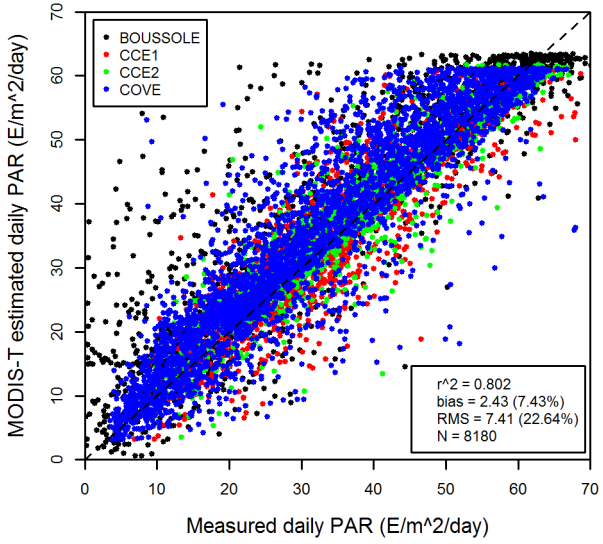
***Figure 5**: Comparison between OBPG daily PAR and in situ measurements (MC-corrected) in clear sky conditions at the COVE, CCE-1, CCE-2, and BOUSSOLE sites.*

Comparison of OBPG daily PAR with in situ data (MC-corrected), all cases









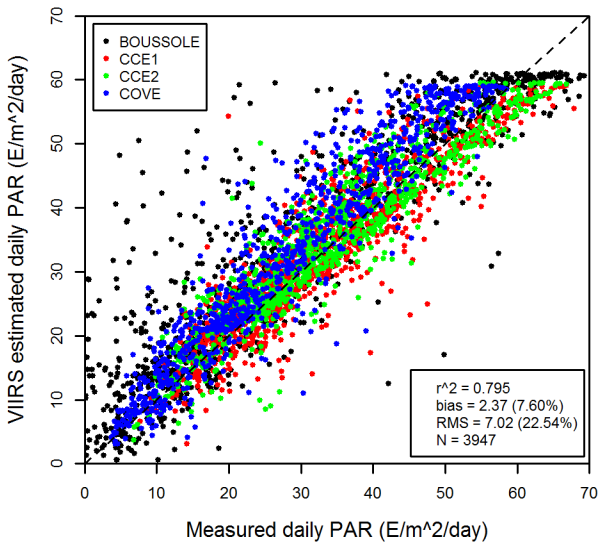


***Figure 6**: Comparison between OBPG daily PAR and in situ measurements (MC-corrected) in both clear and cloudy sky conditions at the COVE, CCE-1, CCE-2, and BOUSSOLE sites.*

Comparison statistics for daily PAR from OBPG vs. in situ data

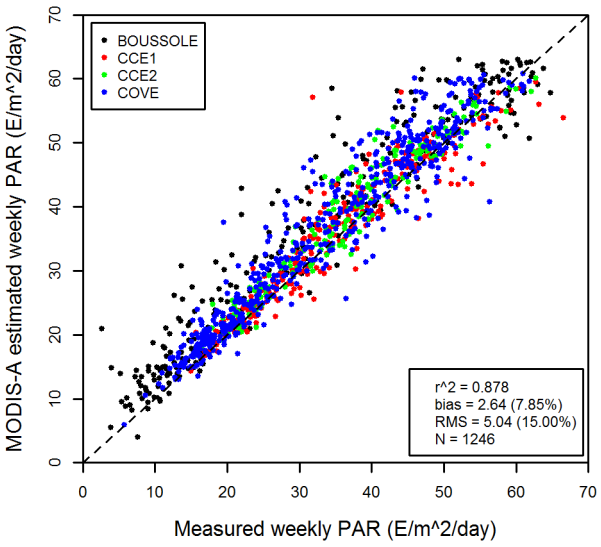
***Table 3a**: Daily PAR comparison statistics, OBPG calculations vs. in situ measurements (MC-corrected) at COVE, CCE-1, CCE-2, and BOUSSOLE sites, clear sky cases.*

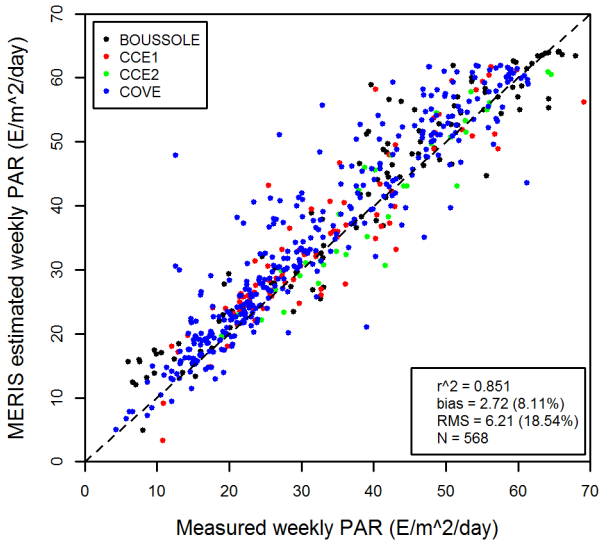
	r^2	bias	Percent bias	RMS	Percent RMS	N
MERIS	0.965	-0.17	-0.40%	2.45	5.71%	135
MODIS-A	0.966	-0.66	-1.46%	2.52	5.57%	687
MODIS-T	0.966	-0.62	-1.39%	2.48	5.54%	657
SeaWiFS	0.933	-2.74	-6.37%	3.53	8.21%	291
VIIRS	0.926	-2.23	-4.78%	3.48	7.44%	262

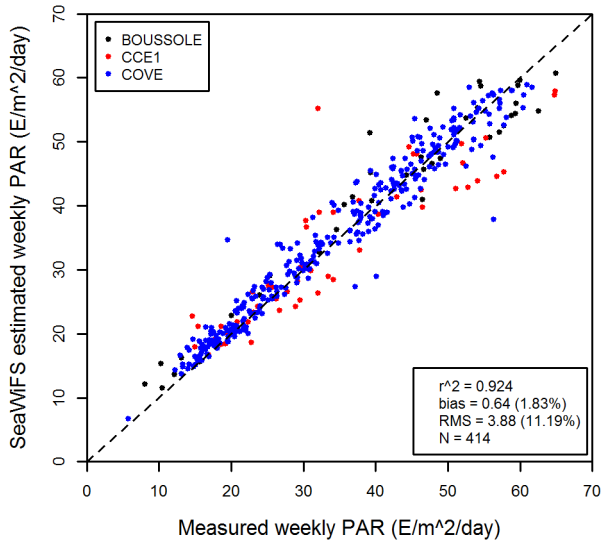
***Table 3b**: Same as Table 3a, but all cases.*

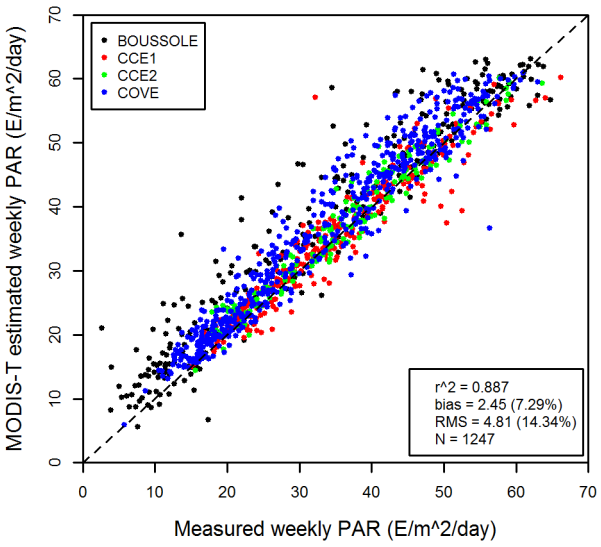
	r^2	bias	Percent bias	RMS	Percent RMS	N
MERIS	0.816	2.59	8.12%	7.32	22.94%	1318
MODIS-A	0.795	2.59	7.97%	7.64	23.48%	8005
MODIS-T	0.802	2.43	7.43%	7.41	22.64%	8180
SeaWiFS	0.832	0.75	2.21%	6.76	19.78%	2847
VIIRS	0.795	2.37	7.60%	7.02	22.54%	3947

Comparison of OBPG weekly PAR with in situ data (MC-corrected), all cases









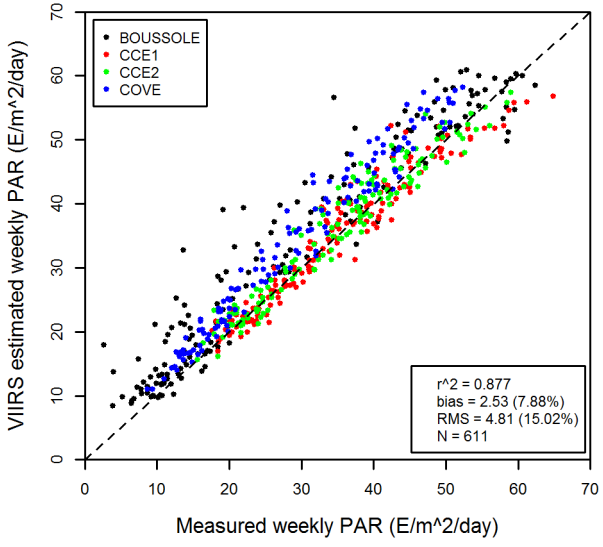
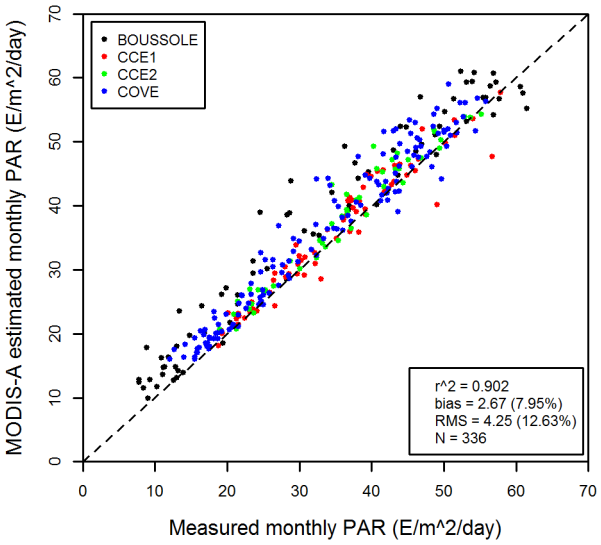
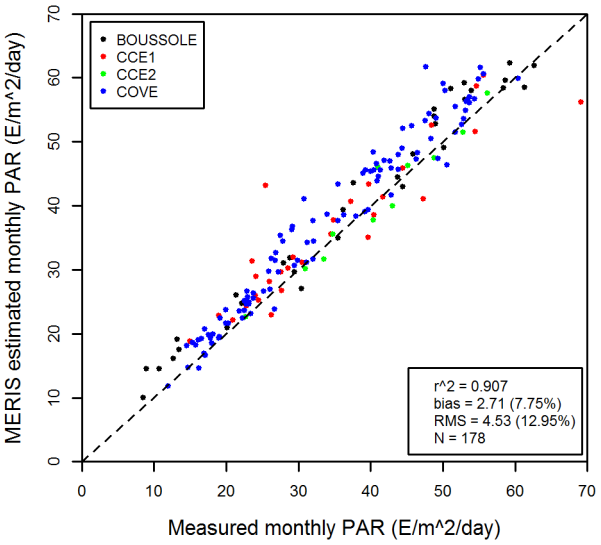
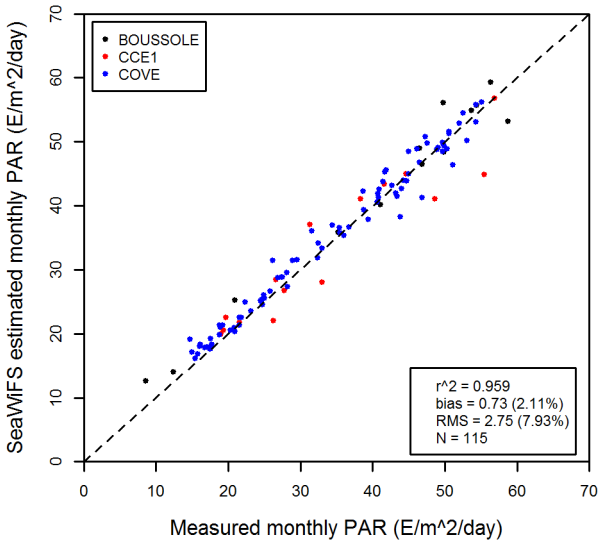


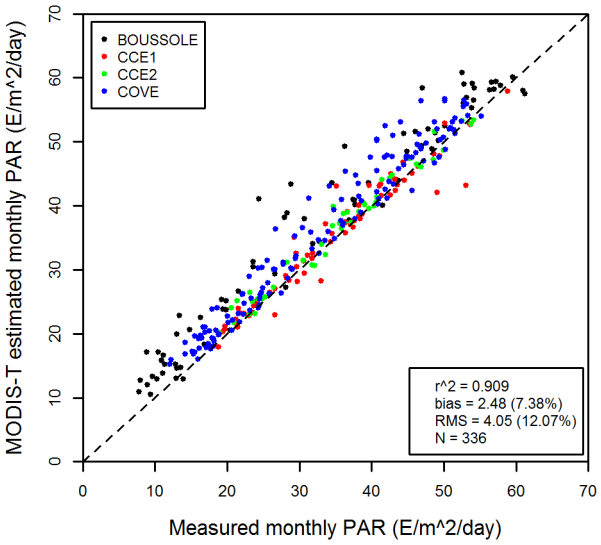
***Figure 7**: Comparison between OBPG weekly PAR and in situ measurements (MC-corrected) in both clear and cloudy sky conditions at the COVE, CCE-1, CCE-2, and BOUSSOLE sites.*

Comparison of OBPG monthly PAR with in situ data (MC-corrected), all cases









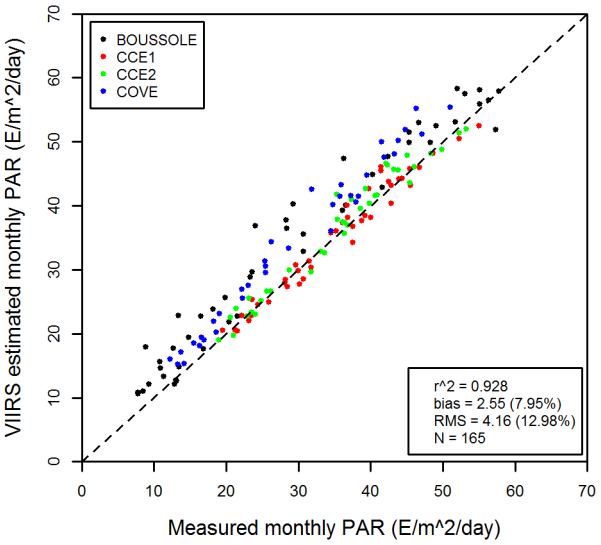


***Figure 8**: Comparison between OBPG monthly PAR and in situ measurements (MC-corrected) in both clear and cloudy sky conditions at the COVE, CCE-1, CCE-2, and BOUSSOLE sites.*

Comparison statistics for weekly and monthly PAR from OBPG vs. in situ data

***Table 4a**: Weekly PAR comparison statistics, OBPG calculations vs. in situ measurements (MC-corrected) at COVE, CCE-1, CCE-2, and BOUSSOLE sites, all (clear and cloudy) cases.*

	r^2	bias	Percent bias	RMS	Percent RMS	N
MERIS	0.851	2.72	8.11%	6.21	18.54%	568
MODIS-A	0.878	2.64	7.85%	5.04	15.00%	1246
MODIS-T	0.887	2.45	7.29%	4.81	14.34%	1247
SeaWiFS	0.924	0.64	1.83%	3.88	11.19%	414
VIIRS	0.877	2.53	7.88%	4.81	15.02%	611

***Table 4b:** Same as Table 4a, but monthly PAR.*

	r^2	bias	Percent bias	RMS	Percent RMS	N
MERIS	0.907	2.71	7.75%	4.53	12.95%	178
MODIS-A	0.902	2.67	7.95%	4.25	12.63%	336
MODIS-T	0.909	2.48	7.38%	4.05	12.07%	336
SeaWiFS	0.959	0.73	2.11%	2.75	7.93%	115
VIIRS	0.928	2.55	7.95%	4.16	12.98%	165

Monthly PAR time series at the evaluation sites (satellite, in situ)

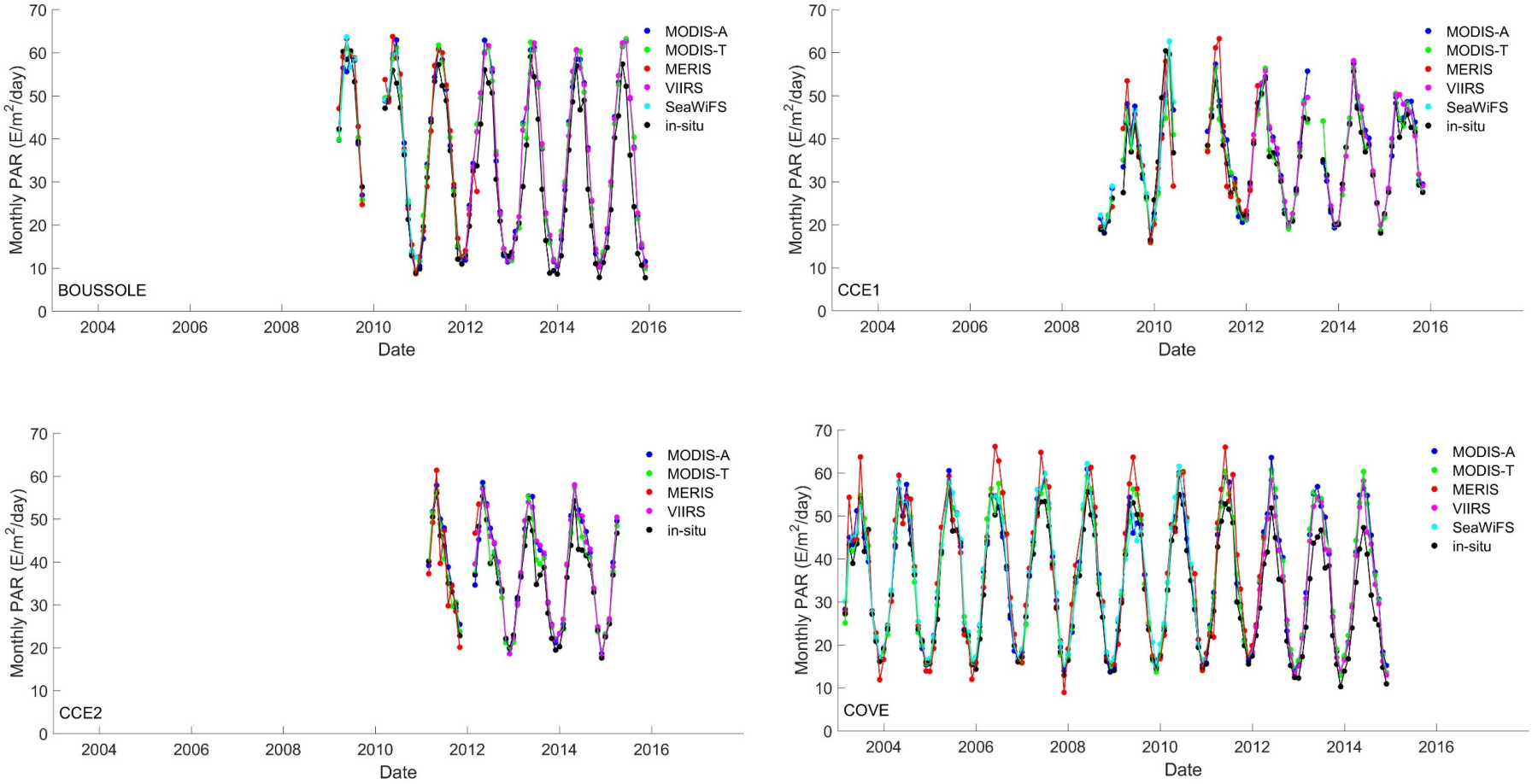
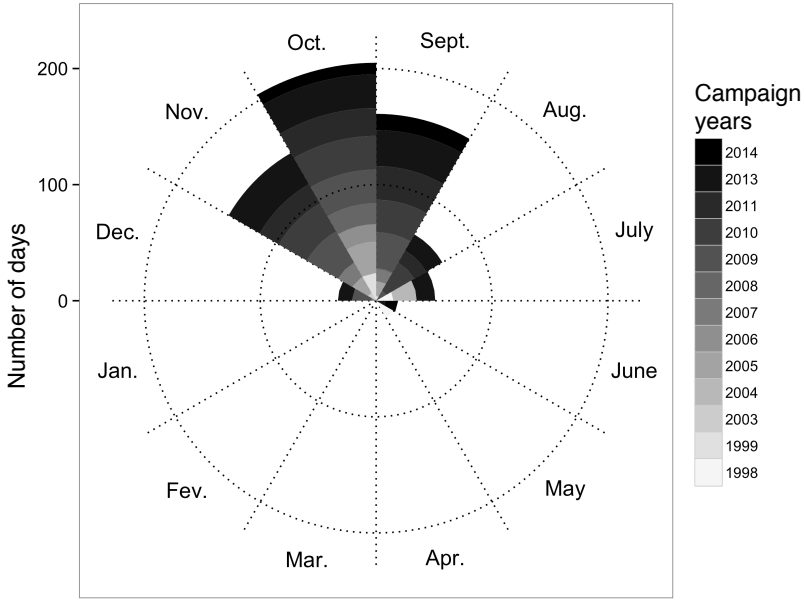


***Figure 9**: Time series of satellite-derived (MERIS, MODIS-T, MODIS-A, SeaWiFS, and VIIRS) and measured monthly PAR at the BOUSSOLE, CCE-1, CCE-2, and COVE sites.*

Evaluation of OBPG daily PAR in the Arctic



Cruise or Program	Year	Instrument	Measurements	Months	Number of days
The NOrth Water (NOW)	1998	LI-COR 192SA[a]	PAR	4,6	32
	1999	LI-COR 192SA	PAR	8-10	29
Canadian Arctic Shelf Exchange Study (CASES)	2003	GUV-510[b]	PAR	10	7
	2004	GUV-510	PAR	6	20
MALINA	2009	LI-190SA[c] SUB-OPS[d]	PAR Spectral	8	23
TARA OCEAN	2013	C-OPS[e]	Spectral	5-12	105
VITALS	2014	C-OPS	Spectral	5	11
ArcticNet (AN)	2005	LI-190SA	PAR	8-10	56
	2006	LI-190SA	PAR	9	15
	2007	LI-190SA	PAR	8,10-11	28
	2008	LI-190SA	PAR	8-9	19
	2009	LI-190SA	PAR	7-11	95
	2010	C-OPS	Spectral	7-10	113
	2011	C-OPS	Spectral	7-10	84
	2013	C-OPS	Spectral	8-10	43
	2014	C-OPS	Spectral	8-9	24

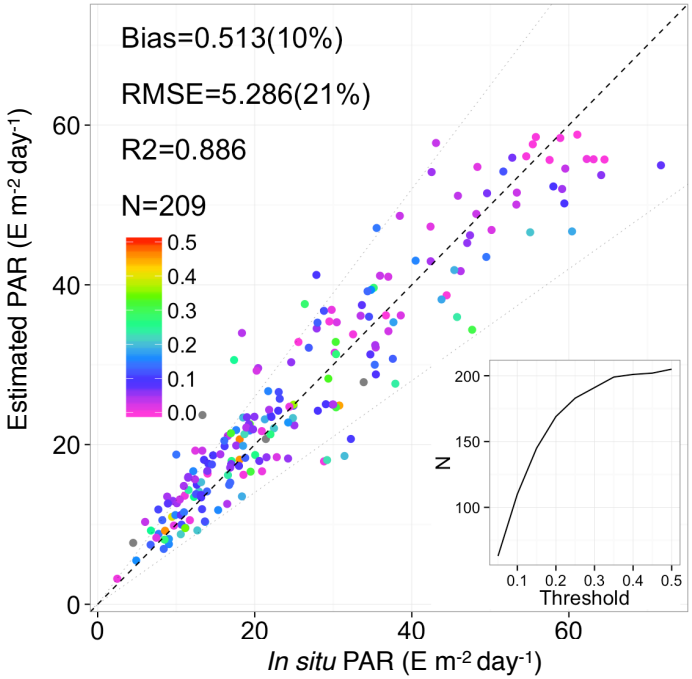


***Figure 10**: Top right: Summary of field campaigns during which PAR was measured continuously. Top Left: Yearly distribution of PAR measurements. Bottom left: Scatterplot of in situ daily PAR versus satellite-derived daily PAR using the OBPG method. The dot colors correspond to CV(intraday) and the inset is a cumulative frequency distribution of the number of matchups as a function of CV(intraday) threshold. 95% of the match-ups show CV(intraday)<30%.*

(Laliberté, Bélanger, Frouin, RSE, 2016, in press.)

Taking into account cloud diurnal variability using ISCCP data

-The albedo of the cloud/surface system, A, can be approximated by $NA_c + A_s$, where A_c is the cloud albedo. It is replaced in the daily integration scheme by A':

$$A' = (A - A_s)\,[N_{ISCCP}(t)A_c(\tau_{c\text{-}ISCCP}(t))]/[A_c(\tau_{c\text{-}ISCCP}\,(t_{obs}\,))N_{ISCCP}(t_{obs})] + A_s$$

where t_{obs} is the satellite observation time, and N_{ISCCP} and $\tau_{c\text{-}ISCCP}$ are the ISCCP fractional cloud coverage and cloud optical thickness (280 km, 3-hour).

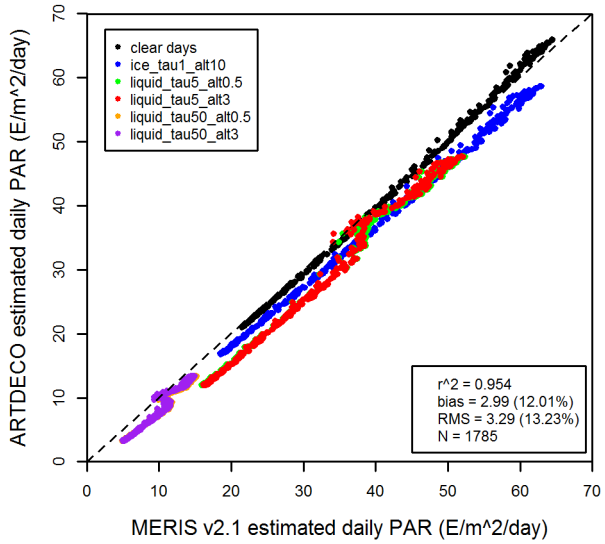
***Table 5a**: Weekly PAR comparison statistics, MERIS v2.1 calculations vs. in situ measurements (MC-corrected) at COVE, CCE-1, CCE-2, and BOUSSOLE sites, all (clear and cloudy) cases. No statistical cloud correction.*

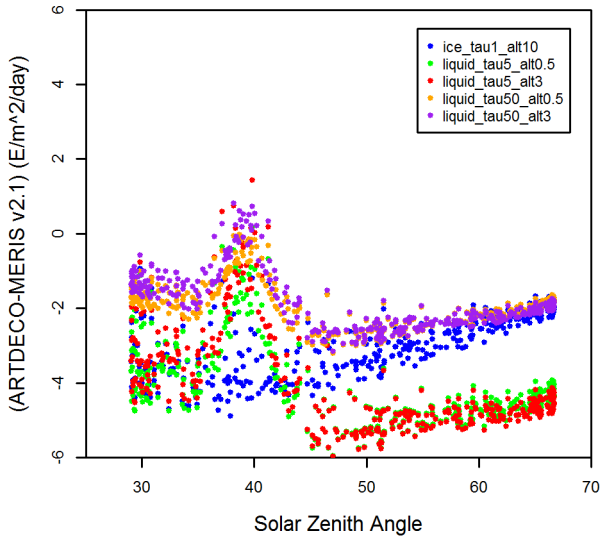
	r^2	bias	Percent bias	RMS	Percent RMS	N
daily	0.801	3.27	9.57%	8.10	23.74%	2187
weekly	0.873	3.38	9.79%	5.97	17.33%	656
monthly	0.907	3.28	9.46%	4.78	13.80%	182

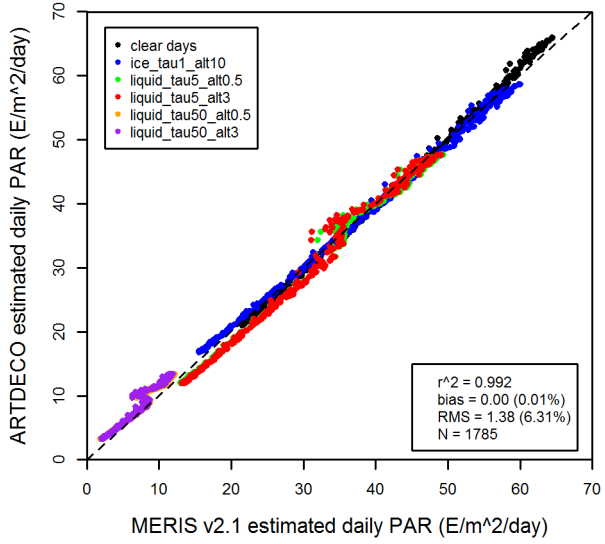
***Table 5b**: Same as Table 5a, but with cloud correction.*

	r^2	bias	Percent bias	RMS	Percent RMS	N
daily	0.794	2.65	7.77%	8.50	24.90%	2187
weekly	0.875	2.78	8.00%	5.90	17.11%	656
monthly	0.914	2.68	7.74%	4.47	12.89%	182

Modeling errors in cloudy conditions







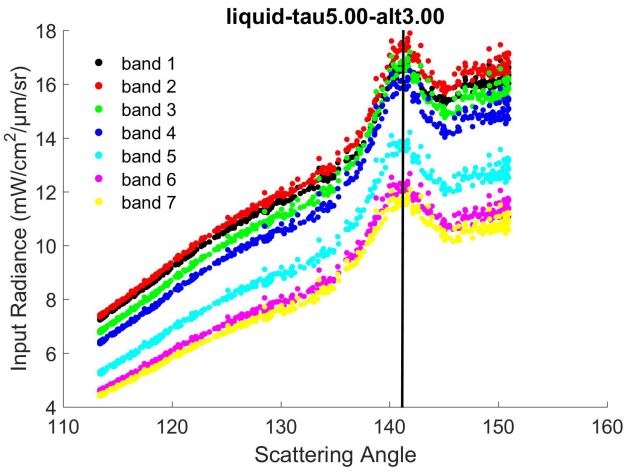


***Figure 11**: ARTDECO simulations of daily PAR for clear sky and various liquid and ice cloud situations versus MERIS 2.1 estimates (using ARTDECO-simulated MERIS radiance). MERIS 2.1 overestimates systematically in cloudy conditions. Bias can be reduced by adjusting reflectance/albedo factor.*

SUMMARY

-Extensive evaluation of the OBPG SeaWiFS, MODIS, MERIS, and VIIRS PAR against multi-year in-situ measurements at BOUSSOLE, CCE-1, CCE-2, and COVE sites has revealed RMS differences of 6.8-7.3 E/m^2/Day (19.8-23.5.%) and 2.8-4.5 E/m^2/Day (7.9-12.9%) and biases of 0.7-2.6 E/m^2/Day (2.2-8.1%) and 0.7-2.7 E/m^2/Day (2.1-7.7%) on daily and monthly time scales, respectively.

-Similar comparison statistics has been obtained during field campaigns in the Arctic, i.e., a RMS difference of 21% and a bias of 10% for daily PAR from SeaWiFS and MODIS.

-PAR tends to be underestimated in clear sky conditions and overestimated in cloudy conditions. Bias can be reduced by adjusting the clear sky model and the cloud bidirectional factor to convert reflectance of the cloud/surface system to albedo.

-Bias is significantly reduced by taking into account diurnal variability of clouds using ISCCP 280 km, 3-hour products, but RMS difference is increased for daily PAR.

FUTURE IMPROVEMENTS

-Adjusting clear sky model, by comparing PAR estimates with "exact" calculations.

-Using look-up table generated from "exact" calculations for converting the cloud/surface reflectance to albedo.

-Using Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2) products, available at 1/2 x 2/3 degree every 3 hours for the day of the satellite observation to account for cloud diurnal variability.